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PLANAR THERMOMETRY IN SOOTING TRANSIENT DIFFUSION FLAMES

(ARO Grant/Contractor No. DAAG55-98-1-0222)

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SUMMARY/OVERVIEW:

Recent computational and experimental studies have shown that conditions exist where the assumption that flamelets respond quasi-steadily to the unsteady strain rates of the turbulent flow-field is invalid [1-4]. If the turbulent Reynolds number is sufficiently large, there exists a range of eddy sizes where the characteristic turnover times of the smallest eddies are comparable to the diffusion times of the laminar flamelets. This also leads to a wide range of characteristic frequencies. Therefore, it is necessary to investigate the frequency response of flamelets to extend the applicability of the flamelet model. The purpose of this investigation was to quantify the response of the reaction-zone temperature and thickness and the strain rate to a time varying flow field.

TECHNICAL DISCUSSION:

A counterflow diffusion burner was used to model a flamelet in the mixing zone of a turbulent reacting flow field. The temperature field in the reaction zone was experimentally determined using two-line OH planar laser-induced fluorescence (PLIF) thermometry [5-7]. Particle image velocimetry (PIV) was used to quantify the velocity and strain rate relationships between measured parameters as a function of flow rate oscillation frequency. Simultaneous with velocity, the OH-field width was measured using PLIF. Reaction-zone thickness was characterized by the full width at half maximum (FWHM) of the OH field [8].

An unsteady flow field was imposed on the counterflow diffusion flame by providing a sinusoidal voltage to the speakers capping plenums located at the entrance to both the fuel and air tubes [9]. Velocity, temperature, and relative [OH] measurements were made as a function of initial steady strain rate (SSR) and forcing frequency. In general, these measurements were made at four temporal locations within the sinusoidal voltage oscillation applied to the speakers: 1) zero amplitude with positive slope, designated *0+*; 2) maximum amplitude, designated *Max*; 3) zero amplitude with negative slope, designated *0–*; and 4) minimum amplitude, designated *Min*. The forcing frequencies considered in this study were 30, 50, 100, 200 and 500 Hz. Results for three flow conditions are reported here and these flows are defined by their measured steady strain rate (SSR), which is defined as the gradient of the air-side axial velocity just prior to the heat release zone.

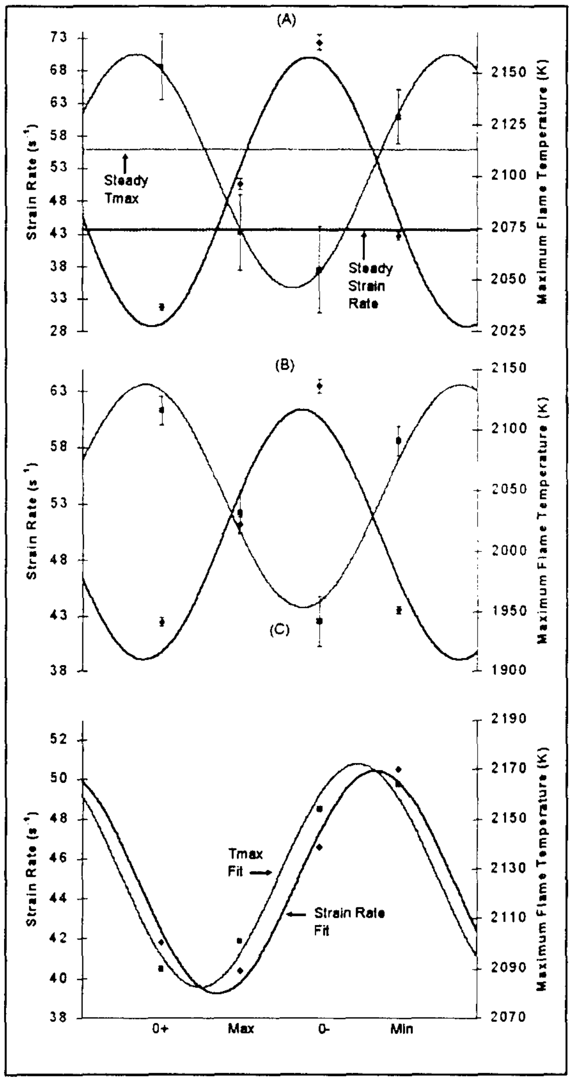

Figure 1: Maximum reaction-zone temperature, Tmax (Boxes), and instantaneous strain rate (Diamonds) at 30 Hz (A), 50 Hz (B), 200 Hz (C) at the four phases. The error bars represent twice the standard deviation of the mean.

The measured strain rates and the maximum reaction zone temperatures, T_{max}, are plotted in Figure 1 for a SSR of 44 s^{-1} at various forcing frequencies. Note that the temperature and velocity measurements were not simultaneous; rather, the PIV measurements were coupled with a single OH PLIF measurement.

At a forcing frequency of 30 Hz (Figure 1 A), the measured strain rate increases between the temporal locations of *0+* and *0–* from 30 s^{-1} to 73 s^{-1}. During this period T_{max} decreases from 2153 K to 2055 K. Then, between locations *0–* and *Min*, the strain rate decreases to 41 s^{-1} and T_{max} increases to 2129 K. At this forcing frequency, the flame appears to be responding in a quasi-steady manner, i.e., with increasing strain rate, T_{max} decreases, and when the strain rate decreases, the T_{max} increases. However, for steady strain rate, the T_{max} continuously decreases with increasing strain rate (decreasing Damkohler number) due to increasing thermal and species concentration gradients.

As the forcing frequency is increased to 50 Hz (Figure 1 B), the measured strain rate is found to increase from 38 s^{-1} to 64 s^{-1} between the *0+* and *0–* locations, while T_{max} decreases from 2116 K to 1942 K. Between the *0–* and *Min* phases, the strain rate decreases to 41 s^{-1} and T_{max}

increases to 2091 K. Thus, as evidenced by this phase relation between imposed strain and T_{max} (i.e., ~180° out of phase), the flame is responding in a quasi-steady manner at both 30 and 50 Hz.

The flame behavior shows unsteadiness when the forcing frequency is increased to 200 Hz, as illustrated in Figure 1 (C). The strain rate and the maximum reaction zone temperature are approximately in phase at the 200 Hz oscillation frequency, which is a significant departure from quasi-steady behavior. This result illustrates the diffusion limited frequency response of the reaction zone. Essentially, the flame will respond to the reactants delivered to the flame front. Convective velocities away from the flame front and diffusive velocities near the reaction zone govern the transport of these reactants. Effectively, the diffusion zone is the bottleneck for reactant delivery. No matter what the rate of change of reactants delivered to the edge of the convective-diffusive zone, these reactants still must travel through the diffusive zone. Thus, as the time necessary to travel through the diffusive zone becomes larger relative to the convective velocities cycle time, a phase lag shows up equal to the diffusion time.

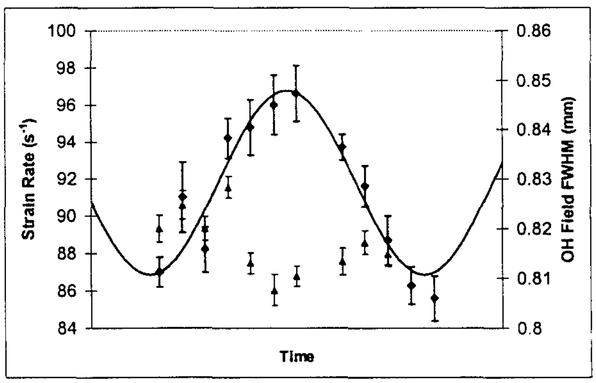

Figure 2: High-resolution strain rate (Diamonds) and OH-field width (Triangles) for a SSR 84 s^{-1} at 500 Hz.

Figure 2 shows the results of a SSR 84 s^{-1} case with a 500 Hz oscillation. The measured strain rate response is reasonably sinusoidal, but no discernable trends are seen in the OH-field response. This would suggest that at this oscillation amplitude and frequency, the changes are undetectable with the resolution used for these measurements. Given the strain rate and OH-field information, an attempt was made to determine if these measured parameters could be used to derive collapsed non-dimensional data plots.

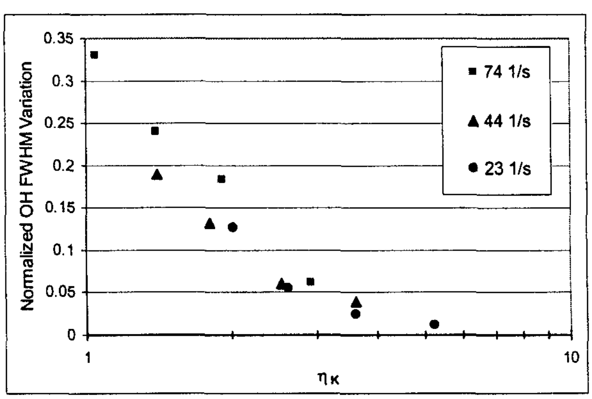

Figure 3: Normalized amplitude of the OH width oscillation as a function of the Stokes parameter.

In a recent numerical investigation, Egolfopoulos and Campbell [3] were able to correlate the variation in maximum flame temperature with a dimensionless frequency, a so-called Stokes parameter η_K, defined as,

$$\eta_K = \left(\frac{\pi f}{K}\right)^{1/2} \qquad (1)$$

Where, f is the forcing frequency and K is the cycle mean strain rate. This comparison can also be made with the variation in reaction-zone width. In Figure 3, the variation in thickness of the OH zone through the oscillation (amplitude of the oscillation) normalized by the mean value is plotted against the logarithm of this Stokes parameter. All the data from the four forcing frequencies (30, 50, 100 and 200 Hz) and three different initial strain rates (23, 44, and 74 s^{-1}) collapse onto a single line with a fairly steep negative slope. At the largest η_K, however, the slope magnitude appears to decrease, perhaps due to the limited spatial resolution of the OH PLIF system. The Stokes parameter ranges from about 1 to 6 in these experiments, which is similar to the results reported in [3]. Fundamentally, this plot illustrates that the OH-field width oscillations are attenuated in a predictable fashion with increasing frequency for the conditions illustrated. This illustrates the tendency for diffusion processes to smear gradients, which is well illustrated by Stokes second problem. For the condition shown in Figure 2, the Stokes parameter is ~ 4.4 and based on the Stokes plot, the normalized OH FWHM variation would be ~ 0.018. As a result of the dramatically reduce oscillation strength, which is a function of frequency, the fluctuations of the reaction zone thickness were not resolvable at the 500 Hz oscillation.

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